BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B69 04109

SUBJECT: Analysis of AAP Orbital Assembly Electrical Power Systems - Case 620

DATE: April 29, 1969

FROM: L. L. Wang

ABSTRACT

A model has been developed to permit analysis of the Orbital Assembly Electrical Power System (EPS) for the AAP missions. Two power sources, the Airlock Module voltage regulators and the Service Module fuel cell assemblies, are considered.

The use of the equivalent circuit for the systems network together with equivalent source voltages and impedances permits simulation of the total EPS when interconnected for power transfer. Numerical data have been obtained to gain a better understanding of the overall EPS performance while power is being transferred between modules.

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MEMORANDUM FOR FILE

INTRODUCTION

Two power sources are considered in this analysis of the AAP Orbital Assembly Electrical Power System -- the Airlock Module (AM) voltage regulators that transfer power from the solar array or AM batteries to the system and the Service Module (SM) fuel cell assemblies (FCA) where electrical energy is produced by the reaction of hydrogen and oxygen. Two identical, parallel distribution systems are used to connect the sources and distribute power to the individual loads. In this analysis the assumption is made that the distribution systems are equally loaded.

Using the schematic of each distribution system given in Reference 1, the equivalent circuit has been found and is shown in Figure 1. The regulators and the FCA's are represented by equivalent voltage sources. The loads are treated as linear impedances. A set of loop equations is written to solve for loop currents. However, the FCA's possess a nonlinear voltage-current relationship. An iterative linear analysis is therefore used to determine the loop currents. The iteration procedure will be discussed in detail.

A computer program has been written to obtain numerical results. The available data on the power requirements for most modules in the AAP Orbital Assembly give only mission average, worst-orbit average, and maximum loads. The exception is the CSM for which North American Rockwell has generated AAP load profiles.

ELECTRICAL POWER SYSTEM ANALYSIS

The equivalent circuit for each distribution system in the Orbital Assembly is shown in Figure 1. Each load in the power system has been considered as an equivalent load impedance. The AM voltage regulator is represented by an equivalent voltage source with a no-load voltage V_R and a source impedance R_R.

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The FCA is also represented by an equivalent voltage source with a no-load voltage V_{FC} and a source impedance R_{FC}. Because the actual fuel cell voltage and internal impedance are not linear with current, the procedure developed in the next section is used to iteratively solve the set of linear equations:

$$[Z] \times [I] = [V] \tag{1}$$

[Z] is a 8 by 8 impedance matrix:

$$[Z] = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & \cdots & Z_{18} \\ Z_{21} & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ Z_{81} & \cdots & \cdots & \cdots & Z_{88} \end{bmatrix}$$

where from Fig. 1:

$$\begin{aligned} Z_{11} &= R_R + R_3 + R_{12} + R_{ES} + R_4 + R_1 \\ Z_{21} &= Z_{12} = -(R_3 + R_{12} + R_{ES} + R_4) \\ &\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ &\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ Z_{88} &= R_{FC} + R_{11} + R_{13} + R_{SM} \end{aligned} \tag{2}$$

R_{SM}, R_{CM}, R_{AM}, R_{MD} -- are the equivalent load impedances for the Service Module, Command Module, Airlock Module, Multiple Docking Adapter, and so on. The expression for R_{FC} is given in the following section:

[V] is a column vector of voltage sources and can be written:

$$[V] = [V_1, V_2, V_3, - - - V_8]$$

where

$$\begin{aligned} V_1 &= V_R \\ V_2 &= V_3 = V_4 = V_5 = V_6 = V_7 = 0 \\ V_8 &= V_{FC} \end{aligned} \tag{3}$$

The expression for V_{FC} is given in the following section.

[I] is a column vector of loop currents,

$$[I] = [I_1, I_2, I_3, - - I_8]$$

which can be solved by using Equation (1):

$$[I] = [Z]^{-1} \times [V] \tag{4}$$

Equation (4) is solved iteratively with R_{FC} and V_{FC} re-evaluated at each iteration step until convergence is obtained. The sign and magnitude of each loop current will indicate the exact performance of the power system. For instance, the total power delivered by the FCA (P_{FC}) or the total power delivered by the AM regulator (P_R) can be calculated:

$$P_{FC} = 2 \times [I_8 V_{FC} - I_8^2 (R_{11} + R_{FC})] \qquad (5)$$

$$P_R = 2 \times [I_1 V_R - I_1^2 (R_R + R_1)] \qquad (6)$$

where the factor of 2 arises because we have treated one of the two distribution systems.

EQUIVALENT CIRCUIT OF THE FUEL CELL POWER SUPPLY

The equation which relates the FCA output voltage to current, elapsed operating time, and degradation rate is*: (Ref. 2)

$$V = [V_o - aI - b(c + I)^{\frac{1}{2}} - Dt]N \qquad (7)$$

where

I = Current

D = Degradation rate

t = Elapsed operating time

N = Number of cells per FCA

V_o, a, b, c are constants.

---

* Temperature effects are ignored because the fuel cell temperature will be stabilized within ± 5°F during the mission.

In order to incorporate this equation into the set of linear loop equations, (1) or (4), we can write Equation (7) as

$$V = V_F - R_F I \tag{8}$$

which represents an equivalent voltage source with an open circuit voltage V_F and source impedance R_F. However, due to the nonlinear term $(c + I)^{\frac{1}{2}}$, V_F and R_F are not constants. Hence a numerical iteration procedure must be employed. First we assume V_F and R_F are constants and use Equation (4) to determine I, then successively correct the values of V_F and R_F by using the previously evaluated I until the desired accuracy is reached.

To insure fast convergence of the iteration scheme, let

$$I = \beta + \tilde{I}$$

where β is a positive constant to be chosen such that

$$\frac{\tilde{I}}{c + \beta} << 1$$

Then the term $(c + I)^{\frac{1}{2}}$ is expanded into a power series and is written as follows

$$
\begin{aligned}
(c + I)^{\frac{1}{2}} &= (c + \beta + \tilde{I})^{\frac{1}{2}} \\
&= (c + \beta)^{\frac{1}{2}} \left(1 + \frac{\tilde{I}}{c + \beta}\right)^{\frac{1}{2}} \\
&= (c + \beta)^{\frac{1}{2}} \left(1 + \frac{1}{2} \frac{\tilde{I}}{c + \beta} A\right) \\
&= (c + \beta)^{\frac{1}{2}} \left(1 + \frac{1}{2} \frac{I - \beta}{c + \beta} A\right) \qquad (9)
\end{aligned}
$$

where

$$
\begin{aligned}
A = {} & 1 - \frac{1}{4} \frac{\tilde{I}}{c + \beta} + \frac{1}{8}\left(\frac{\tilde{I}}{c + \beta}\right)^2 \\
& + \text{---} \frac{(\frac{1}{2} - 1)(\frac{1}{2} - 2) \text{--} (\frac{1}{2} - n)}{(n+1)!} \left(\frac{\tilde{I}}{c + \beta}\right)^n + \text{---} \qquad (10)
\end{aligned}
$$

Substituting (9) into (7) and rewriting as Equation (8), we obtain:

$$
V_F = [V_o - b(c + \beta)^{\frac{1}{2}} + \frac{b\beta}{2}(c + \beta)^{-\frac{1}{2}} A - Dt]N \qquad (11)
$$

$$
R_F = [a + \frac{b}{2}(c + \beta)^{-\frac{1}{2}} A]N \qquad (12)
$$

V_F and R_F depend implicitly on I through the parameter A. It is clear that a fast convergent series A in powers of I insures the fast convergence of the iteration procedure used to solve Equation (4).

The internal impedence of the FCA, R_{FC}, called for in Equation (2) is equal to R_F (Eq. 12) when two FCA's are being operated. If all three FCA's are operating in parallel, then $R_{FC} = 2/3\ R_F$. The no-load FCA voltage, V_{FC} called for in (3) is equal to V_F (Eq. 11). The current I_8 called for in (4) is equal to I in (8).

RESULTS

The system has been analyzed for average, maximum, and minimum mission power requirements, which are taken from Reference 3 and presented in Table 1. Figure 2 shows the initial power supplied by three 31-cell FCA's and two 31-cell FCA's as a function of AM regulator voltage when mission-average loads exist. The three-FCA configuration will supply approximately 250 watts more than the two-FCA configuration for any given regulator voltage setting. Since the average fuel cell power is limited to 1800 watts during a 56-day mission by cryogenic supplies, the two 31-cell FCA configuration is preferable. It is also desirable for reliability and system flexibility.

Figure 3 shows the total power delivered by the fuel cells as a function of mission time for mission average loads. At the end of the 56-day mission, the FCA output voltage will have decreased due to degradation. When connected into the network with the AM regulators also supplying power, the power supplied by the FCA's will decrease by as much as 400 watts over the length of the mission. This means that increasing amounts of power must be transferred from the AM to the CSM to meet mission average requirements.

Figure 4 shows the power supplied by AM EPS and the FCA's as a function of AM regulator voltage at the beginning of a CSM mission. Maximum and average CSM power requirements have been considered. At the maximum CSM power level, the total system power requirement at any AM voltage regulator setting is the sum of the dashed P_R and P_{FC} curves in Figure 4. The AM regulators will be overloaded if P_R is greater than the capability of the AM power system (this capability is a function of the sunline-orbit plane angle and the time-degradation of the array or the power capacity of the AM batteries). Matching P_R (the requirement) with the capability yields a voltage setting that will prevent overload. Operation of the third FCA will raise the P_{FC} curve and therefore lower the P_R curve, thus permitting higher AM voltage settings without overload.

Figure 5 shows the power requirement from the FCA's as a function of CM power requirement for three values of AM regulator voltage and two values of SM power requirement. For an increase in CM power requirement of 3000 watts, the FCA's must supply 1250 watts while the rest of the power will be supplied by the AM regulators. An increase of 1 volt in the AM no-load regulator setting will reduce the FCA's output by about 260 watts.

Figure 6 shows the effects of the line resistances on the power system, where the maximum CSM power requirement is considered. Line R is the typical value of line resistances given in Ref. 1. Line 2R or line $\frac{1}{2}$R indicates the line resistances being double or half of the values of line R. In other words, the size of the bus wires will also affect the system performance.

DISCUSSION

1. For the 56-day mission, the no-load voltage setting, V_R, of the AM regulators should be initially adjusted higher than 30V in order to limit the FCA's to 1800 watts average power during the entire mission. However, for the 28-day mission since the average power of fuel cell can be 2.25 kw (Ref. 4), the voltage, V_R, can be adjusted lower than in the 56-day mission.

2. The third FCA is necessary to assure adequate power capability throughout the mission in the event of an FCA failure or during periods of maximum power requirements. However, during the average power condition, two 31-cell FCA's are preferable.

1022-LLW-ep

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REFERENCES

1. Minutes of Second AAP Power Systems Working Group Meeting, May 22, 1968.

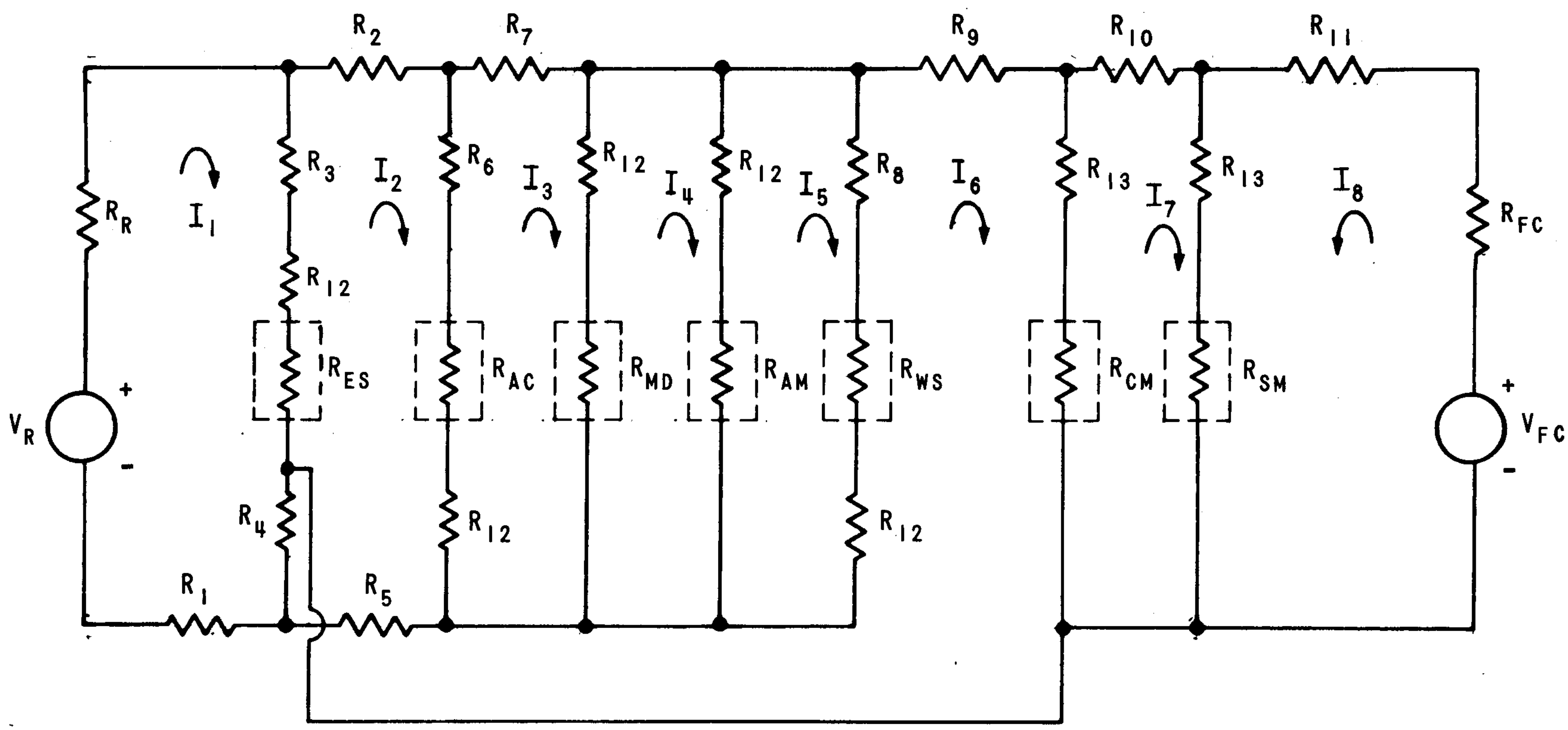
2. AAP CSM Configuration Baseline, NAR SD 68-558, October 7, 1968.

3. AAP Weight and Performance Review at MSFC, September 26, 1968.

4. Baseline Configuration Definition AAP-1 through AAP-4, NASA, February 1, 1969.

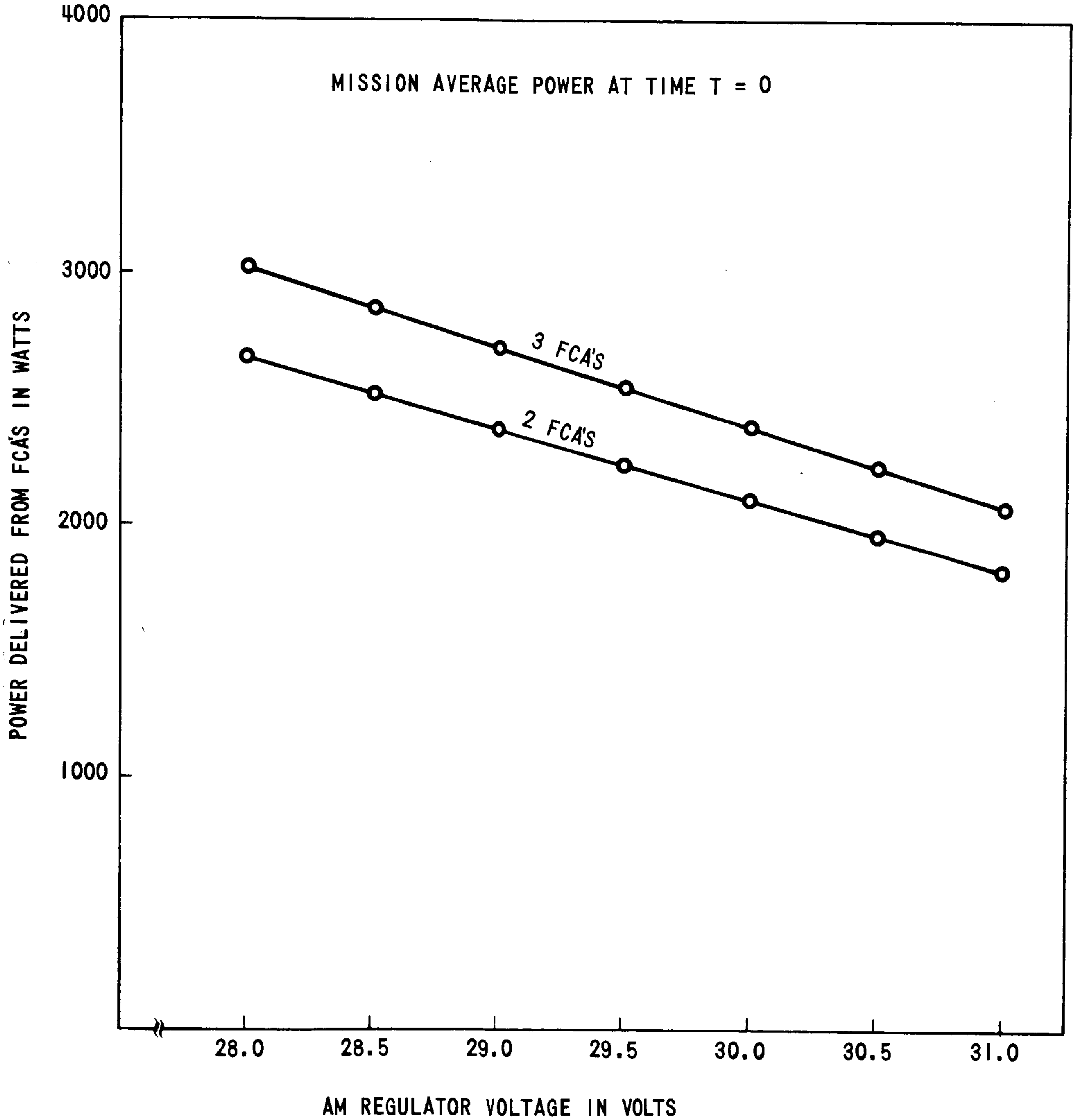
CASE	P_{SM}, WATTS	P_{CM}, WATTS	P_{AM}, WATTS	P_{MDA}, WATTS	P_{OWS}, WATTS	P_{EXP}, WATTS	P_{TOTAL}, WATTS
AVERAGE MISSION POWER	1125	1125	755	200	1866	61	5132
MAX MISSION POWER	1063	3475	875	200	1866	170	7649
MIN MISSION POWER	0	1155	755	200	1866	61	4037

TABLE I
MISSION POWER REQUIREMENT



R2
R7
R9
R10
R11
R3
R6
R12
R12
R8
R13
R13
RR
RFC
I1
I2
I3
I4
I5
I6
I7
I8
R12
RES
RAC
RMD
RAM
RWS
RCM
RSM
VR
VFC
+
-
+
-
R4
R12
R12
R1
R5

FIGURE 1



MISSION AVERAGE POWER AT TIME T = 0
4000
3000
2000
1000
POWER DELIVERED FROM FCA'S IN WATTS
3 FCA'S
2 FCA'S
28.0
28.5
29.0
29.5
30.0
30.5
31.0
AM REGULATOR VOLTAGE IN VOLTS

FIGURE 2

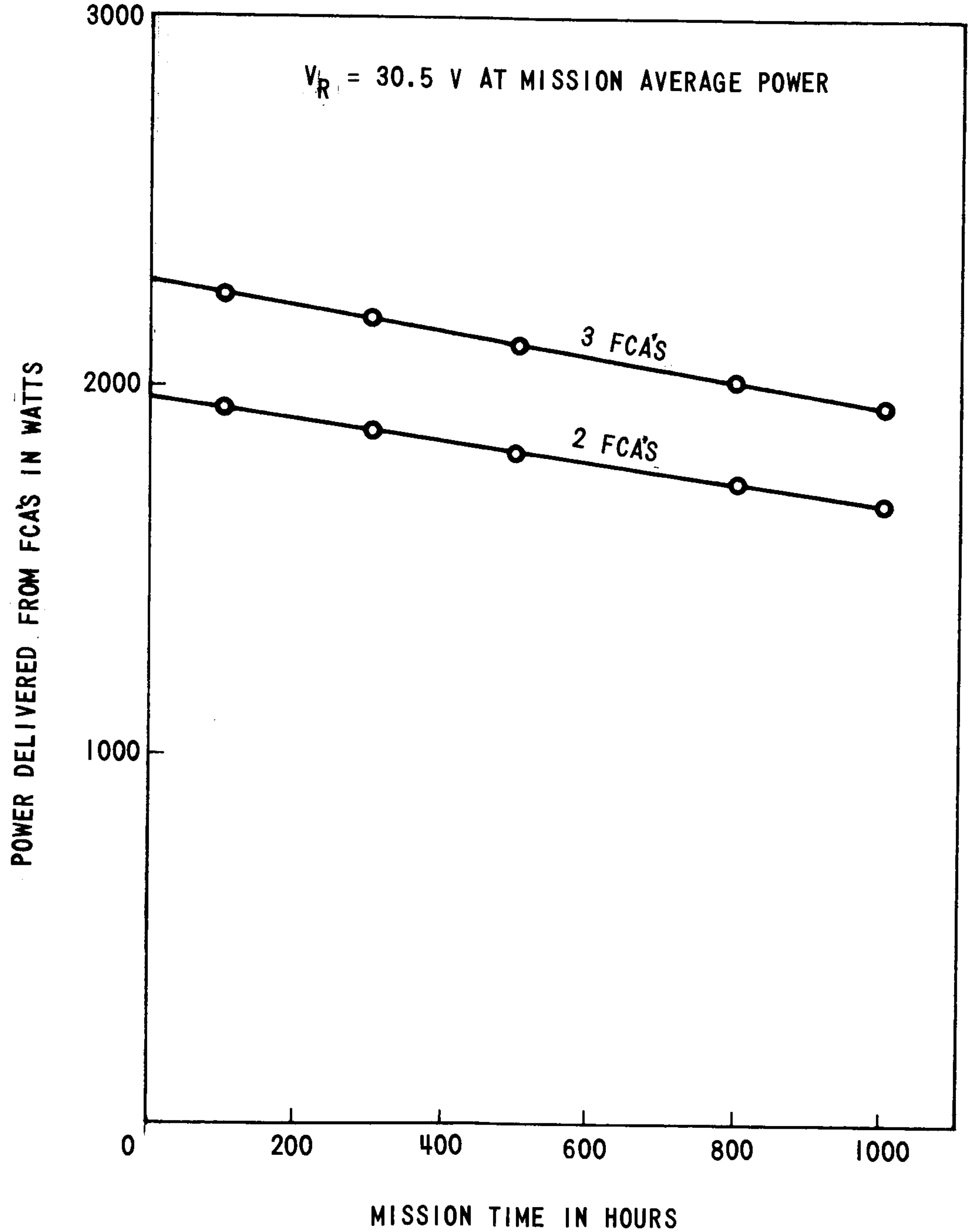

3000
V_R = 30.5 V AT MISSION AVERAGE POWER
3 FCA'S
2000
2 FCA'S
1000
0
200
400
600
800
1000
POWER DELIVERED FROM FCA'S IN WATTS
MISSION TIME IN HOURS

FIGURE 3

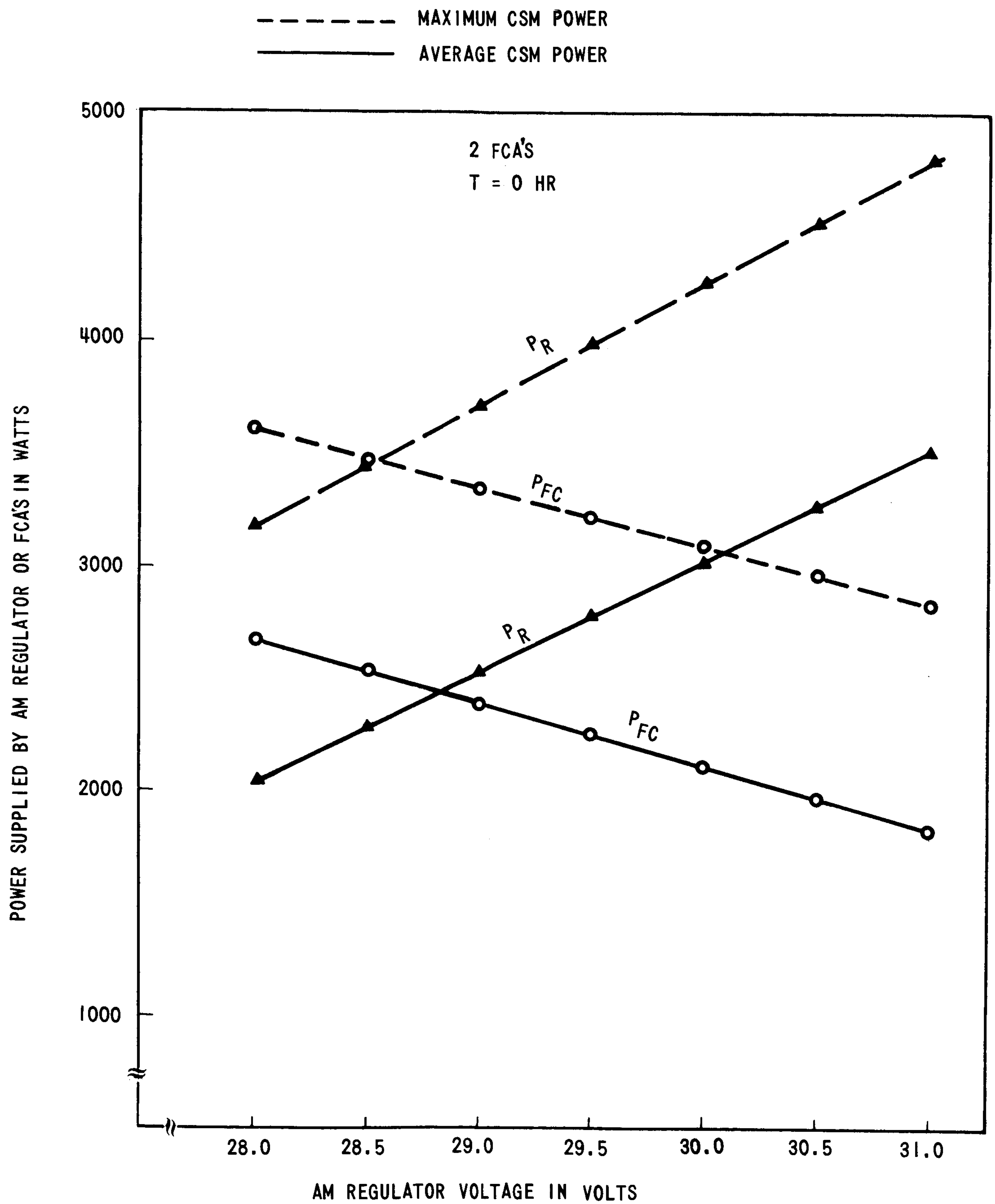
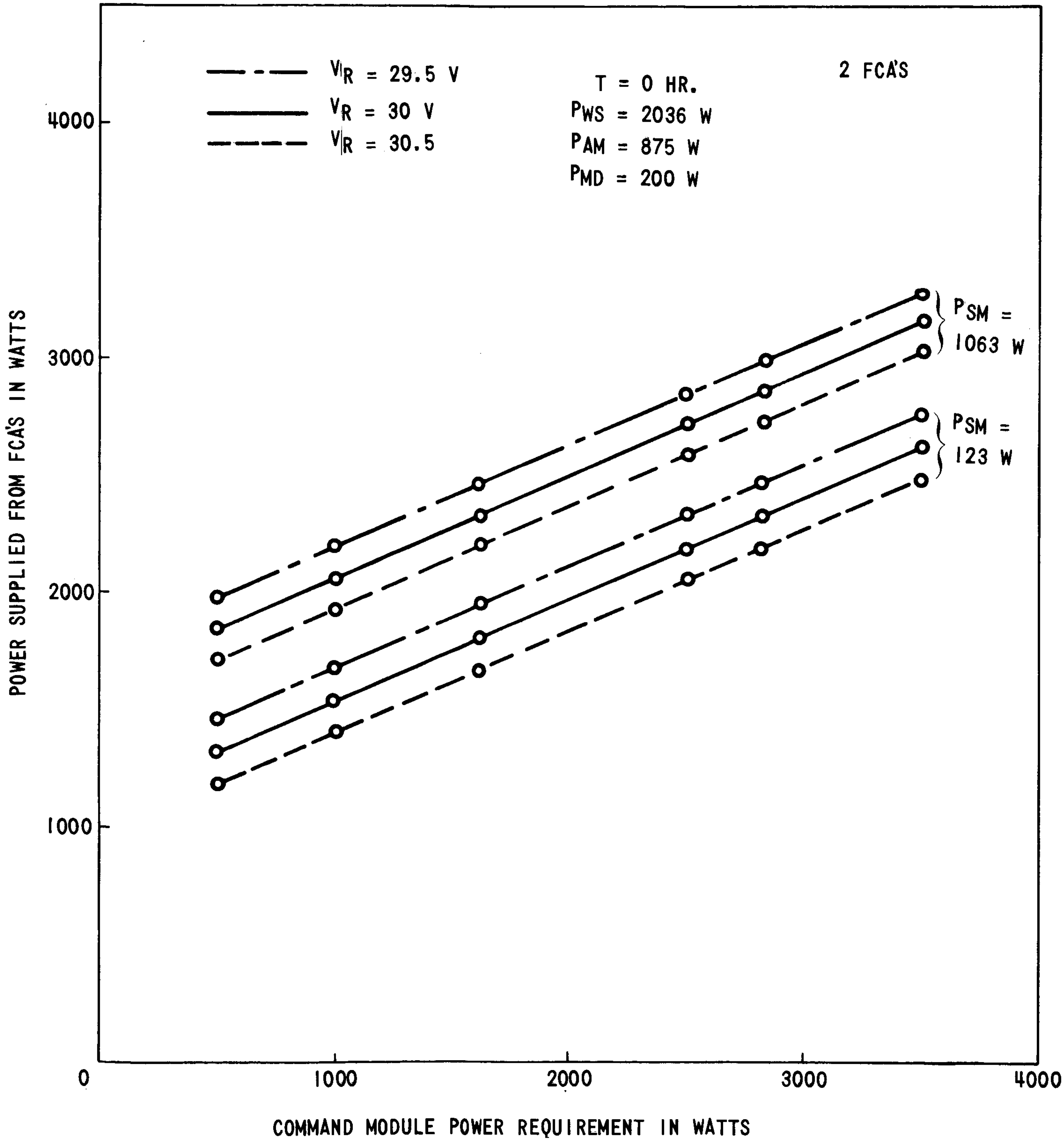

MAXIMUM CSM POWER
AVERAGE CSM POWER
2 FCA'S
T = 0 HR
P_R
P_{FC}
P_R
P_{FC}
5000
4000
3000
2000
1000
POWER SUPPLIED BY AM REGULATOR OR FCA'S IN WATTS
28.0
28.5
29.0
29.5
30.0
30.5
31.0
AM REGULATOR VOLTAGE IN VOLTS

FIGURE 4



V_R = 29.5 V
V_R = 30 V
V_R = 30.5
T = 0 HR.
P_{WS} = 2036 W
P_{AM} = 875 W
P_{MD} = 200 W
2 FCA'S
P_{SM} = 1063 W
P_{SM} = 123 W
POWER SUPPLIED FROM FCA'S IN WATTS
4000
3000
2000
1000
0
1000
2000
3000
4000
COMMAND MODULE POWER REQUIREMENT IN WATTS

FIGURE 5

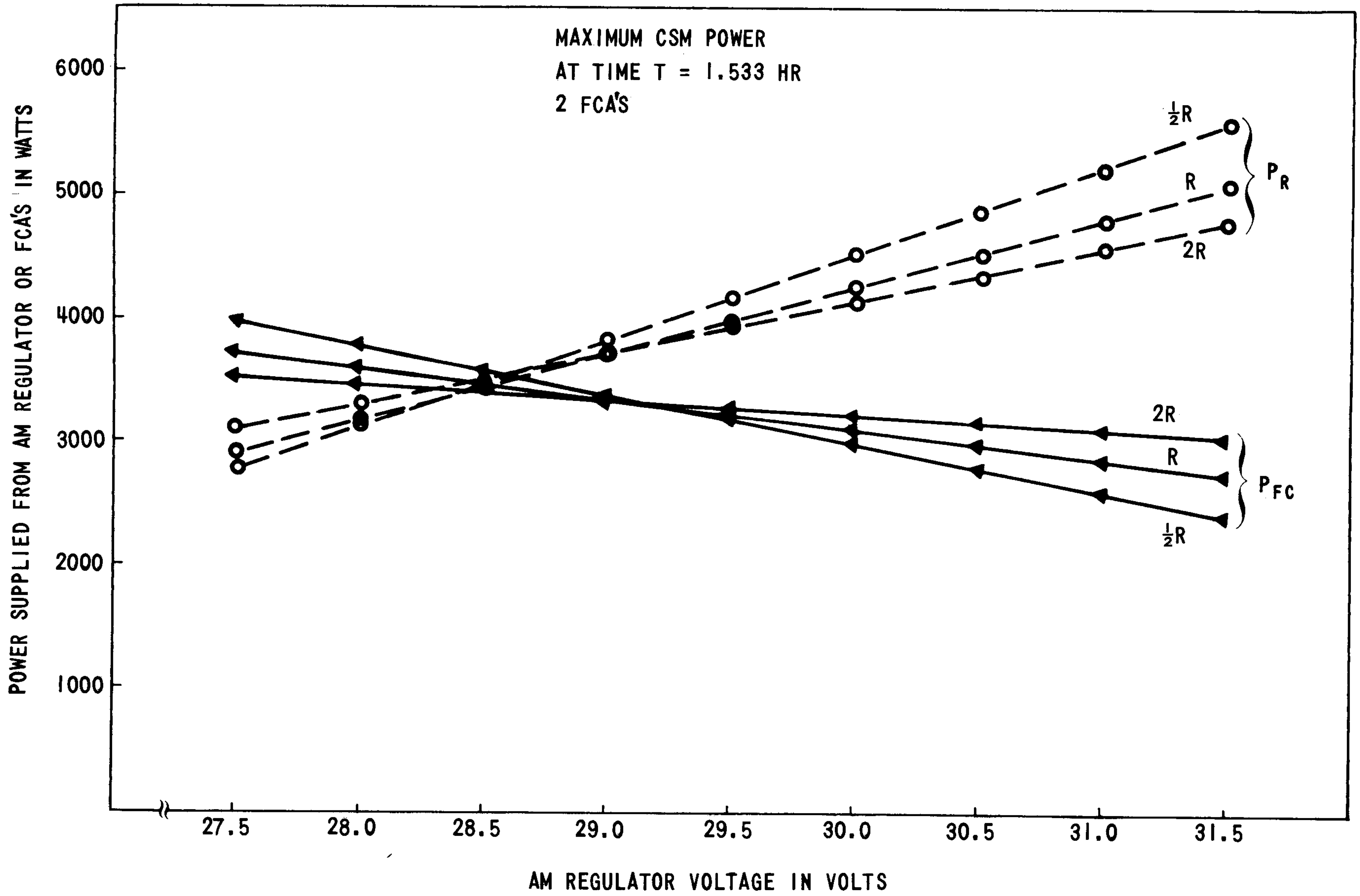

MAXIMUM CSM POWER
AT TIME T = 1.533 HR
2 FCA'S
POWER SUPPLIED FROM AM REGULATOR OR FCA'S IN WATTS
6000
5000
4000
3000
2000
1000
27.5
28.0
28.5
29.0
29.5
30.0
30.5
31.0
31.5
AM REGULATOR VOLTAGE IN VOLTS
½R
R
2R
P_R
2R
R
½R
P_{FC}

FIGURE 6 -

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From: L. L. Wang

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